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FLAMELESS OXIDATION TO REDUCE THERMAL NO-FORMATION

J. A. Wünning and J. G. Wünning

WS Wärmeprozesstechnik GmbH, Dornierstrasse 14, D-71272 Renningen, Germany

Abstract—This report will present a special form of combustion, called flameless oxidation. In contrast to the combustion within stabilized flames, temperature peaks can be avoided at flameless oxidation. For that reason, the thermal NO-formation is largely suppressed, even at very high air preheat temperatures. A brief summary of the present NO_x-reducing techniques will be given. The illustration of flameless oxidation will cover the explanation of the basic principle, the presentation of calculated and measured data and the introduction of some application examples. The results are encouraging the assumption that NO-emissions from a wide range of combustion sources could be largely eliminated in the future. Use of burners, operated in flameless oxidation mode in continuous industrial furnaces have proven to be reliable and well accepted for the very uniform product quality by furnace people. © 1997 Elsevier Science Ltd.

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1. INTRODUCTION

The development of efficient, low polluting combustion systems is a major goal of combustion researchers and the manufacturers of combustion equipment. To meet that goal, a good collaboration of basic researchers and design engineers, with the transfer of knowledge from theory and practice in both directions is necessary. For the benefit of energy resources and the environment, it is necessary that the new combustion systems are accepted and used in the industry. That requires, among other things, an affordable price and it must be possible to operate these systems without special expertise.

Nitric oxide could be ranked to the most relevant pollutants, which is even emitted if 'clean gases' like natural gas or hydrogen are used because it can be formed from air nitrogen and oxygen at high temperatures. Within the last years, great progress has been made to reduce nitric oxide, or more general NO_x-emissions, from combustion systems. The use of catalytic converters for the internal combustion engines of automobiles are law in many nations now. Today, nearly every burner manufacturer offers low-NO_x (and even ultra-low-NO_x . . . .) burners, but there is still a great potential for the reduction of pollutants.

Beside energy shortage, which is not perceived by many people, the influence of combustion products on the global climate had become a catchword in the discussion about the combustion of fossil fuels. Although these different arguments for reducing the energy consumption, the clear task of engineers is the development of efficient combustion systems.

Especially at high temperature processes, better efficiency is mostly achieved by air preheating. Therefore, energy of high temperature exhaust gases is transferred to the combustion air in recuperative or regenerative heat exchangers. A consequence of high air preheat temperatures are increased peak temperatures in the flame with an enormous effect on the thermal NO-formation. The target is to overcome the conflict of interest between energy savings and NO-reductions. A new technical form of combustion,

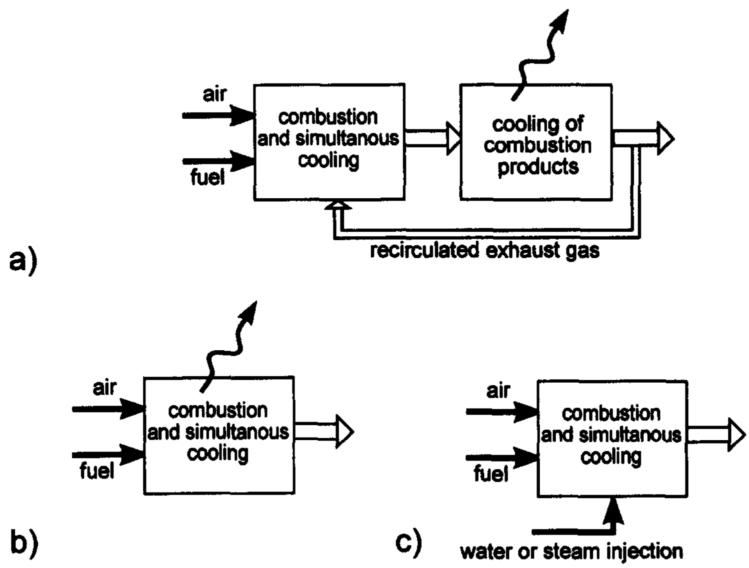

Fig. 1. NO_x-reducing by flame cooling.

applicable to temperatures above self ignition of flammable mixtures, referred to as flameless oxidation, is a very promising solution to this dilemma.

2. STATE OF THE ART

A report about the present and future limitations on nitrogen oxides emissions was given by Bowman,[1] showing that many improvements have to be made, to meet all future limitations on NO_x-emissions. There are three predominantly mentioned sources of nitric oxides from combustion processes:[2]

- prompt NO,
- fuel NO,
- thermal NO,

whereof the thermal NO-formation, described by the 'Zeldovich-mechanism',[3] is the most relevant source for the combustion of clean fuels like natural gas.[4,5] That is particularly true if preheated air is used,[6] causing an increase in combustion temperatures.

The three principle reactions for thermal NO formation are

$$O + N_2 \rightleftharpoons NO + N$$

$$N + O_2 \rightleftharpoons NO + O$$

and

$$N + OH \rightleftharpoons NO + H.$$

Like the name indicates, the mechanism is only relevant at higher temperatures. Considerable NO-emissions can be found if oxygen containing combustion products are exposed to temperatures:

- > 1600 °C for some seconds or
- > 2000 °C for only milliseconds.

Because of that strong temperature influence, most NO-reducing techniques try to cut off peak temperatures, keep the residence time in high temperature areas low and avoid high oxygen concentration in these areas. The following chapters should give a brief explanation of the most common NO_x-reducing techniques. Very often the measures cannot be separated very clearly and often several measure were applied simultaneous.

2.1. *Flame Cooling*

There are many different techniques which could be classified as flame cooling. The aim of flame cooling is to reduce peak temperatures and residence time of combustion products in high temperature areas. Main limits for flame cooling techniques is incomplete combustion and thereby the emission of carbon monoxide. Flame cooling could be achieved by the withdrawal of energy or by mixing of combustion products with cooler recirculated exhaust gas, water or steam.

Figure 1(a) shows the schematic for flame cooling with recirculated exhaust gas. High velocity burners use the high momentum of the flame jet to mix with gases from the combustion chamber. These exhaust gases, entrained in the flame, are cooler than the fresh combustion products in the flame. Heat release during the combustion process (see Fig. 1(b)) happens for almost all flames due to radiation. Enhanced cooling by cooling rods is applied to reduce thermal NO-formation in domestic water heaters or boilers (see Fig. 2). Surface combustion with enhanced radiation is also applied mainly to smaller domestic applications. To improve flame stability and complete combustion, many investigations with catalytic coatings were carried out.

Another way to enhance cooling by flame radiation is the creation of long, luminous sooty flames. Great care has to be taken to avoid soot deposits, soot and

carbon monoxide emission, if that measure is applied. Finally, steam and water injection has to be mentioned as a measure to reduce NO-emissions. Because of the additional energy costs and of practical complication, water and steam injection are not widely employed in thermal equipment.

2.2. *Staging*

Staging is used in various forms to control NO_x-emissions. Thereby a primary combustion zone with nonstochiometric conditions is followed by cooling the combustion products and a secondary combustion zone. Often, air staging is used. That means, the primary combustion takes place under rich conditions and secondary air is injected for the secondary combustion. The cooling of combustion products can be achieved by direct cooling through radiation and convection (see Fig. 3(a)) or by cooling through mixing with recirculated combustion products from further downstream (see Fig. 3(b)).

Staging could be either applied to the burner design itself, or could be achieved by fluid injection through separate pipes. An example for the latter is over- or underfiring in power plant boilers or waste incineration boilers. A burner design for air staging is shown in Fig. 4. The primary combustion takes place in a combustion chamber, where the flame is stabilized by a disk on the gas nozzle. The combustion products enter the furnace with a high velocity of typically 100 m/s. The jet entrains exhaust gases from the furnace to cool down the combustion products. Further downstream secondary combustion takes place with air, injected through concentric arranged nozzles.

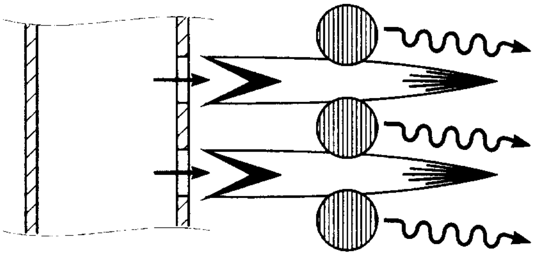

Fig. 2. Flame cooling by flame rods.

2.3. *Exhaust Gas Recirculation*

Exhaust gas recirculation is a very effective method to lower peak flame temperatures and, thereby, thermal NO-formation. At exhaust gas recirculation, the exhaust is not mixed into the flame, but further upstream to combustion air and/or fuel (see Fig. 5). Here, the distinction between external and internal exhaust gas recirculation should be kept in mind. At external recirculation, exhaust gas is taken from the stack and is added, in most cases, to the combustion air. To bring the exhaust gas to the required pressure, a blower or a jet pump has to be used. External exhaust gas recirculation could be applied to existing designs as a low NO_x-expansion.

Internal exhaust gas recirculation is achieved aerodynamically in the combustion chamber by special burner design. A benefit of internal flue gas recirculation is that no additional equipment and piping are required and that there is no negative influence on the efficiency. The latter is especially important for high temperature applications. Flameless oxidation, as later explained in more detail, is also based on internal flue gas recirculation

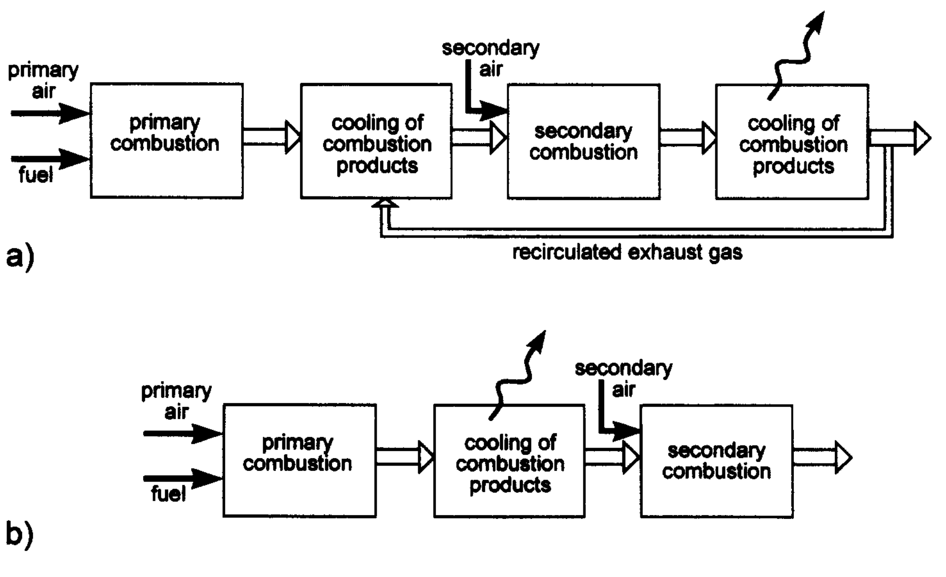

Fig. 3. NO_x-reducing by air staging.

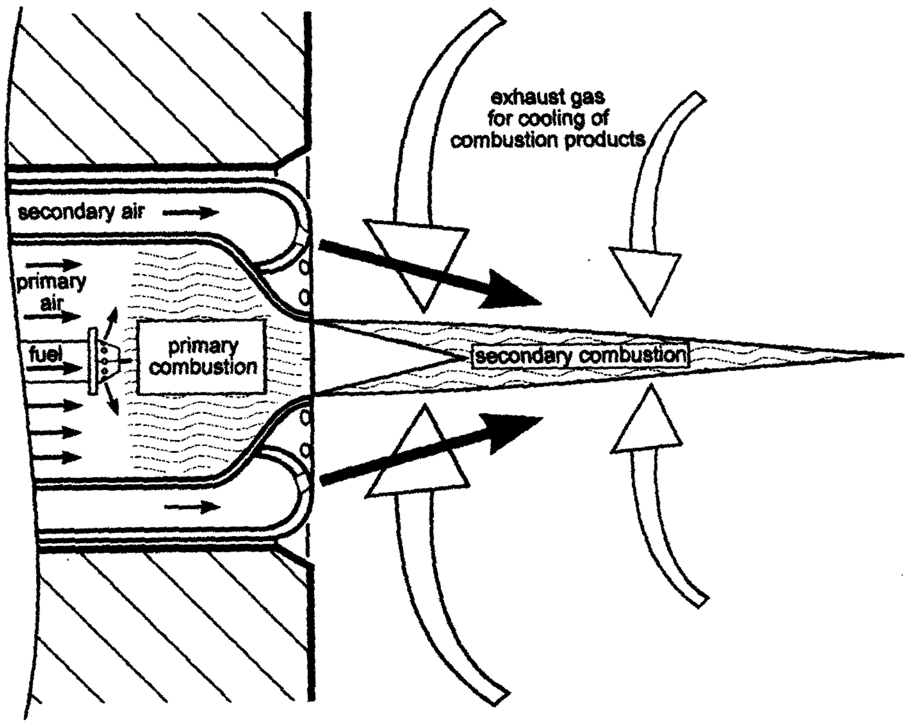

Fig. 4. Burner discharge of a high velocity burner with air staging.

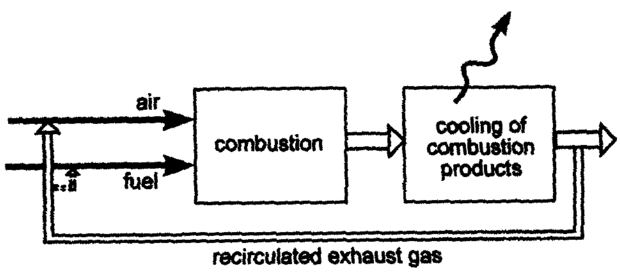

Fig. 5. NO_x-reducing by exhaust gas recirculation.

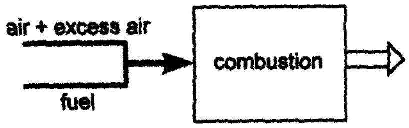

Fig. 6. NO_x-reducing by lean premixed combustion.

2.4. *Lean Premixed Combustion*

Lean premixed combustion has been mainly developed for gas turbine applications.[7] There is no major cooling step involved (see Fig. 6), and combustion takes place in adiabatic conditions. For premixed air and fuel, the adiabatic combustion temperature can be controlled by the amount of excess air. Limitations are given by flame instability and the risk of backfire. Lean premixed combustion could not be applied for very high air preheat temperatures due to the tendency of self ignition.

2.5. *Reburning*

Whereas the previous measures are designed to reduce the formation of nitric oxide, reburning reduces existing nitric oxides. Especially if nitrogen containing fuel is used, the formation of 'fuel NO', often cannot be avoided. In that case, a reburning fuel could be injected to the combustion products to reduce the NO to N_2. The reburning fuel could be either the same fuel as the main fuel, or another fuel. To achieve good results, the reburning process has to take place in a specific temperature range and a good homogeneous mixture has to be provided.[8] Secondary air must be injected further downstream to achieve complete oxidation of the reburning fuel. Because the reburning process could take place in the combustion chamber or further downstream, depending on the process conditions, reburning could be named either a primary or as a secondary measure. Typical steps for a reburning process are shown in Fig. 7. Reburning is

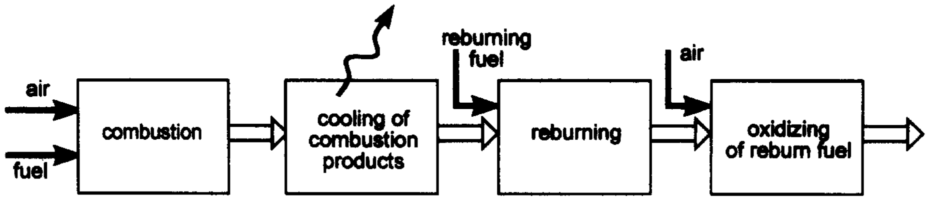

Fig. 7. NO_x-reducing by reburning.

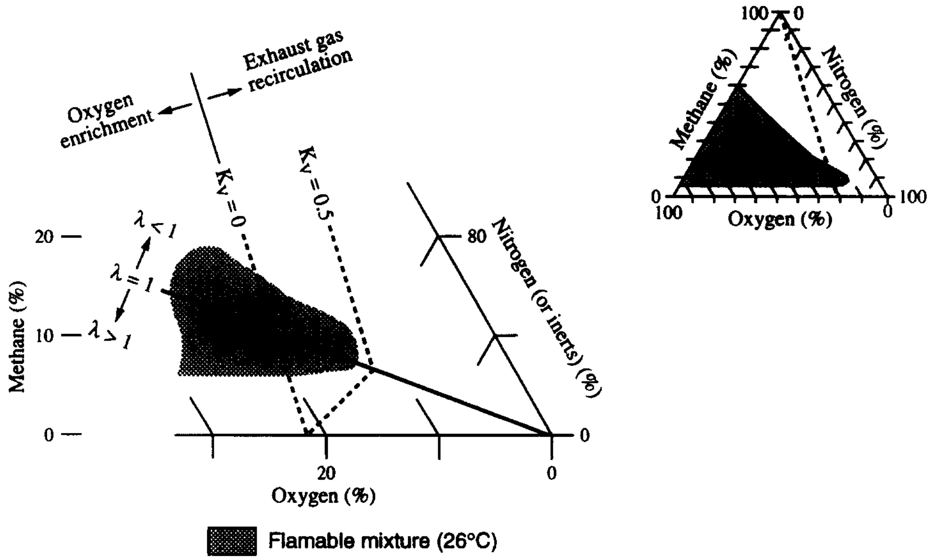

Fig. 8. Flammability limits (data from Zabetakis).

discussed as NO_x-reducing technique for coal fired power plants, waste incineration plants, glass tanks and in chemical plants.

2.6. *Usage of Oxygen as Oxidizer*

The usage of oxygen or oxygen enriched air is considered to be as a measure to reduce fuel consumption and NO_x emissions. The assumption of reducing NO_x-emissions is based on withdrawing all nitrogen from the combustion processes. To realize this condition in practical systems, all of the following conditions must be guaranteed:

- the oxygen must be pure,
- the fuel should not contain any nitrogen, and
- the combustion has to be tight to avoid inleakage of air.

All these prerequisites are hard to achieve in practical systems. Pure oxygen is very expensive and normally not available in large amounts for combustion. Natural gas contains typically 1–14% of nitrogen. If there is any nitrogen available in the combustion chamber, the high combustion temperatures of combustion with oxygen can lead to extremely high NO-emissions,[9] if no special precautions are taken. To judge the environmental advantage of oxygen usage, the energy consumption and the emission of pollutants for oxygen production have to be considered.

2.7. *Secondary Measures*

Secondary measures (exhaust gas cleaning) like SCR (selective catalytic reduction) and SNCR (selective non-catalytic reduction) have no influence on the process itself. These measures can be expanded to existing plants or in cases where producers are concerned about primary measures on their product quality. An example is the glass industry with high NO_x-emissions, but a very sensitive glass melting process. Secondary measures can be expensive and often make up a considerable part of equipment and running costs.

3. FLAMELESS OXIDATION

In contrast to the combustion in stabilized flames, the combustion at flameless oxidation is mixture and temperature controlled, achieved by specific flow and temperature conditions. According to Günther is a prerequisite for a stable flame, balance between flow- and flame-velocity.[10] This is true for premixed as well as diffusion flames. This criteria is dependent on species concentrations, flow velocity, flow field, temperature, pressure and other parameters.[11,12]

Creating flow conditions for flame stabilization, is an essential burner design criterion. Swirl or bluff-body are most often used to create stagnation points or areas of low velocity for stabilization. The species

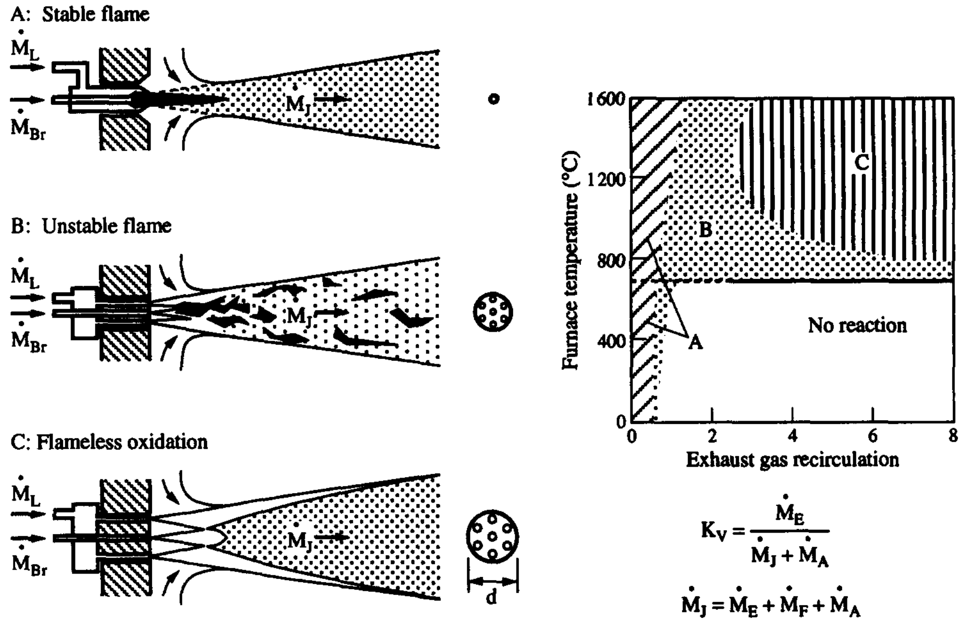

Fig. 9. Stability limits (schematic).

concentration also plays an important role. Air, with an oxygen content of about 21% and many fuels can create a flammable mixture. That is the reason, why flames could be used as a tool by the human race very early.

Exhaust gas recirculation increases the content of inerts of a mixture. Flammabilty limits for combustion of hydrocarbons and air[13] show, that it is possible to achieve flammable mixtures for recirculation rates of $K_V \leq 0.5$ (see Fig. 8). To provide reliable operating conditions in practical systems, exhaust gas recirculation rates of $K_V \leq 0.3$ are used as a NO_x-reducing technique.

Thereby, the recirculation rate is defined as:

$$K_V = \frac{\dot{M}_E}{\dot{M}_F + \dot{M}_A}$$

(subscripts: E – recirculated exhaust gas;

F – fuel; A – combustion air)

(Only exhaust gas recirculated into combustion air and fuel before the reaction (flame front) is considered to be recirculated exhaust gas. The recirculation of hot product inside the burner to improve flame stability is not considered as exhaust gas recirculation.)

It was found,[14] that under special conditions, a stable form of combustion is also possible for much higher recirculation rates. Under ideal conditions, that combustion takes place without any visible or audible flame. For that reason it was named 'Flameless Oxidation'. Figure 9 shows a schematic diagram of the stability limits for different combustion modes. Stable flames 'A' are possible over the whole range of combustion chamber temperature but only for recirculation rates up to 30% (somewhat

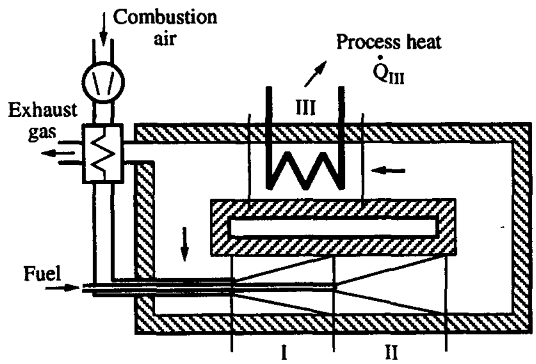

Fig. 10. Idealized process of flameless oxidation.

increased at higher temperatures). For higher recirculation rates, the flame will become unstable 'B', lift off and finally blow out (for temperatures below self ignition). If the furnace temperature and the exhaust gas recirculation are sufficiently high, the fuel can react in the very steady, stable form of flameless oxidation 'C'. As it can be seen from the diagram, it is not possible to operate a burner with flameless oxidation in a cold combustion chamber. Therefore, the combustion chamber must be heated up with flames and then could be switched to flameless oxidation.

A first estimate for the adiabatic temperature of common fuels in the presence of exhaust gas recirculation shows, that for high recirculation rates, the temperature rise during the reaction is only a few hundred Kelvin and the influence of air preheating becomes small.

$$\vartheta_{ad} = \vartheta_0 + \frac{2000\text{K}}{K_V + 1}.$$

(ϑ_0 – temperature of unreacted mixture of exhaust, fuel and combustion air)

By avoiding peak temperatures, the thermal NO-formation can be largely suppressed, even at highest air preheat temperatures.

An idealized process schematic is shown in Fig. 10. In a first step 'I', combustion air is mixed with recirculated exhaust gas. After complete mixing fuel is added in step 'II'. The maximum, or adiabatic temperature rise could be only a few hundred Kelvin, if enough exhaust gas was recirculated and is independent from chemical kinetics. So, the simple assumption of "mixed is burnt" could be applied. In a third step, the energy has to be withdrawn from the combustion products, keeping the temperatures on a certain level to guarantee reaction in step 'II'. Air preheat could be applied, but is not compelling.

The technical realization of the process steps are shown in Fig. 11. The burner has two air supplies to operate in flame mode to heat up the furnace as well as in flameless oxidation mode. At flame mode, fuel is brought by the fuel supply '1' and the gas nozzle '4' into the central primary combustion chamber '5'. The air '2' is supplied also to that chamber. The burner operates like a conventional high velocity burner with a spark plug ignition and a stabilized flame. At the end of the heat up cycle, the air valve at the air supply

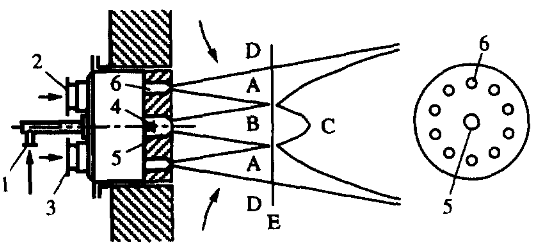

Fig. 11. Burner for flame and flameless oxidation mode.

'2' is closed and then, the air is supplied by a second air supply '3' through air nozzles '6', which are arranged concentric around the combustion chamber '5'. The air jet 'A' aspirates exhaust as well as the fuel jet 'B' from the surroundings 'D'. The reaction in zone 'C' could not take place earlier as when the air and fuel jets meet. At that point, the jets have already mixed with a large amount of exhaust gas. The recirculation rate could be estimated from the geometrical arrangements. For a first estimate, the laws for single free jets[15] could be applied.

Besides the separation of fuel and air supply, there is another way to suppress the spontaneous reaction. That could be done, if the temperature conditions are arranged in a way that the reactions is prevented until enough exhaust is mixed in. For the theoretical considerations, the assumption 'mixed is burnt' could no longer be applied and the chemical kinetic has to be considered. It was found, that flameless oxidation could not only be achieved by separated supplies of fuel and air, but also by a common supply and even for the injection of premixed air and fuel. Under particular conditions, the mixture could be also far off stochiometric. That gives the opportunity to control the temperature in a combustion chamber by the stoichiometric conditions rather than withdrawing energy and to apply flameless oxidation also for adiabatic combustion chambers ($Q_{\mathrm{III}} \to 0$, see Figs 10 and 12).

For a calculation of residence time, pollutant formation and fuel conversion, often the models of plug flow reactor and perfectly stirred reactor are used. For flameless oxidation, the model of a loop reactor was found to be useful[16] (see Fig. 13). The mean residence time and the residence time distribution could be described by the volume flow rate and the recirculation rate K_V. For that reactor type, the plug flow reactor and the perfectly stirred reactor

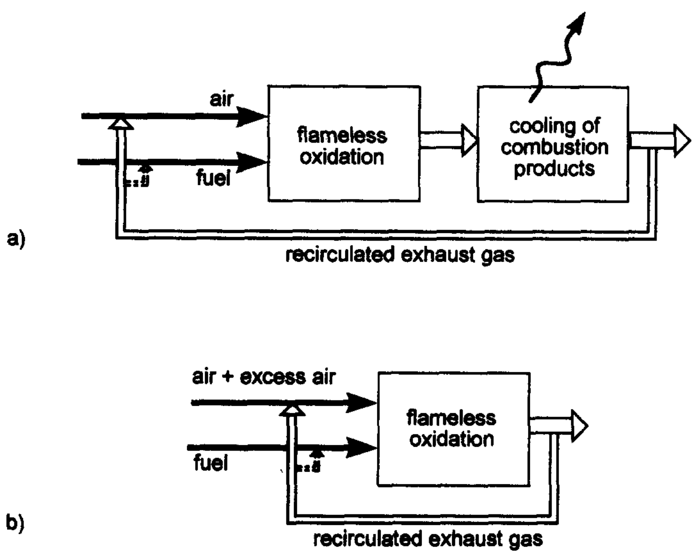

Fig. 12. NO_x-reducing by flameless oxidation: (a) nonadiabatic; (b) adiabatic.

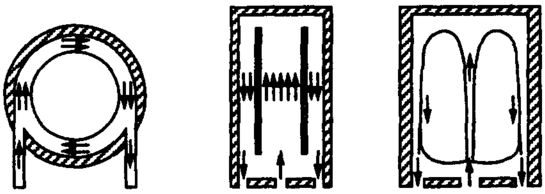

Fig. 13. Examples of loop reactors.

would be the borderline cases (plug flow—$K_V = 0$; perfectly stirred—$K_V \rightarrow \infty$).

4. CALCULATED AND MEASURED DATA

To get a better comprehension of the process of flameless oxidation, flow simulation and field measurements were carried out. The second task was a comparison of calculated and measured data to prove the suitability of computational fluid dynamics as a tool for the design of flameless oxidation burners.

4.1. *Mathematical Modelling*

Commercial CFD-software (computational fluid dynamics) was used to simulate the conditions at flameless oxidation. The software is based on the numerical solution of the Navier–Stokes equations.[17,18] The following models were used for the presented results:

- turbulence — k,ϵ-model[19]
- chemical reaction — one step Arrhenius approach
- radiation — flux-model [20]
- NO-formation — one step Arrhenius approach[21]
- heat transfer — logarithmic wall function[22]
- density — ideal gas law.

A comparison was made for three burners, which would provide the same net heat input (160 kW) for a furnace at a temperature of 1200°C. If a burner with no air preheat is used, a burner capacity of 400 kW is necessary, due to the combustion efficiency of only 40%. Using a very effective recuperator, 600 °C air preheat would be possible and the required capacity would be only 245 kW. A further increase in air preheat temperature could be achieved with a regenerative system. At 950°C air preheat temperature, only 200 kW capacity are required, which is half of the cold air burner.

The temperature field was calculated for these three configurations, assuming the first two burners operating as high velocity burners in flame mode and the third burner in flameless oxidation mode. The results of the calculation are shown in Fig. 14. The cold air burner shows a typical temperature distribution and a peak temperature of 1840°C. Using preheated air for the same burner type would result in a similar temperature distribution, but with a maximum temperature of 2120°C. For the third burner, the air preheat is increased once again, but operating in flameless oxidation mode leads to a maximum temperature of only 1745°C.

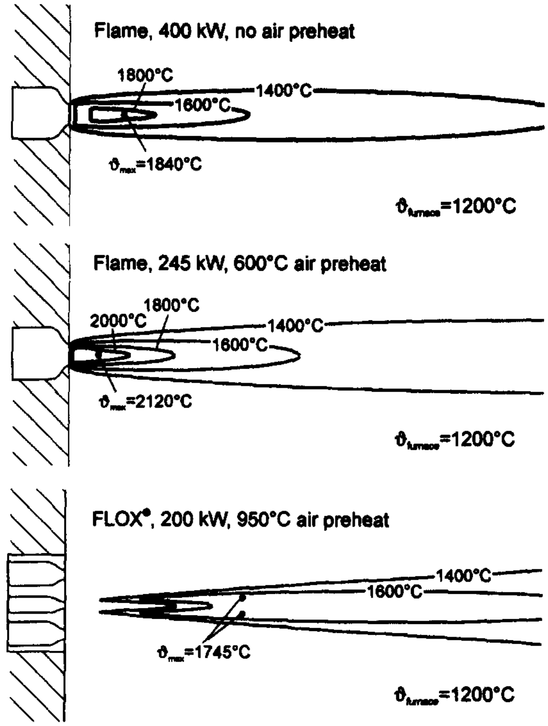

Fig. 14. Temperature distribution for burners with varied air preheat (flame or flameless oxidation mode).

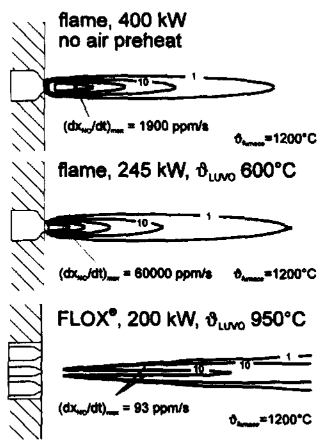

Fig. 15. Local NO-formation for burners with varied air preheat (flame or flameless oxidation mode).

The 1400°C isothermal lines of all three calculations show no big differences. Thus, the other result which can be read from the calculation is, that the main differences among the three burners are related to the near burner field. That is true for the temperatures as well as for the fuel mass concentrations and the flow field. Based on the calculated mean temperatures and species concentrations, the local NO-formation was calculated. The results, presented (as ppm/s—parts per million per second) in Fig. 15, show the strong connection of NO-formation to the peak temperatures. Further calculations were carried out and will be compared to measured data in the next chapter.

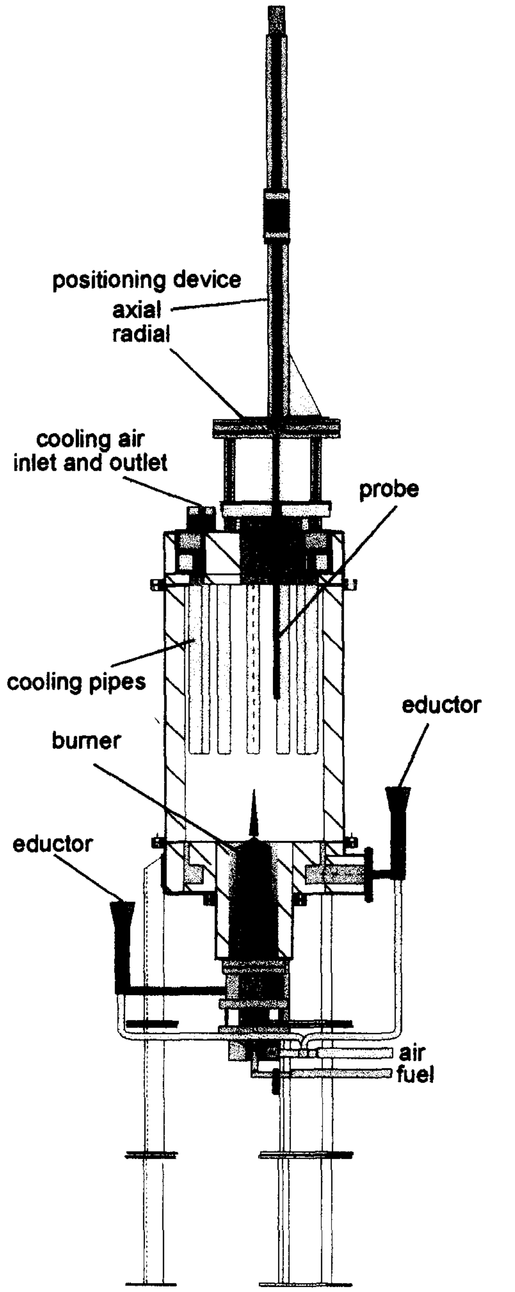

Fig. 16. Test furnace for measuring temperature and velocity fields.

4.2. *Field Measurements*

Field data of the temperatures and velocity were taken in a special combustion chamber, shown in Fig. 16. The recuperative burner (burner with integrated recuperative heat exchanger for air preheat up to 700 °C) was mounted at the bottom of the chamber, firing vertically into a cylindrical, air cooled chamber. The computer controlled positioning devices were mounted at the top, bringing the probe in position with a minimum influence on the flow conditions. Temperatures were detected with a thin

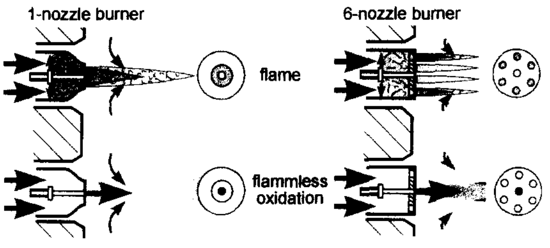

Fig. 17. Principles of test burners.

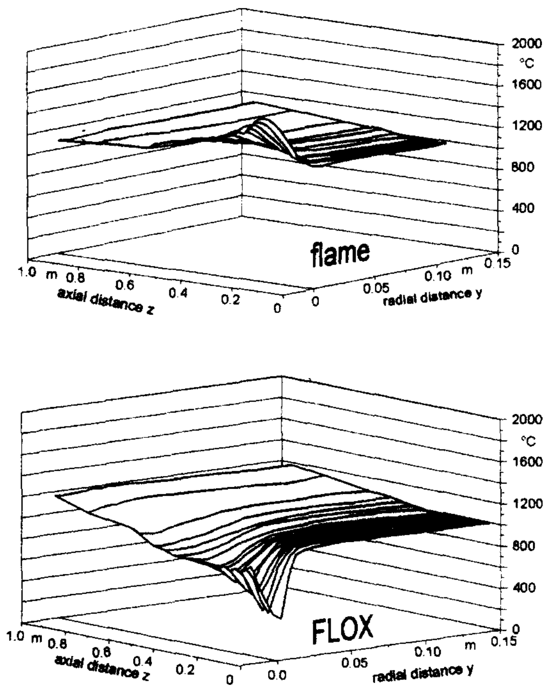

Fig. 18. Measured temperature distribution of 1-nozzle flameless oxidation burner.

(0.05 mm) thermocouple and flow velocity was calculated from the dynamic pressure.

Two types of burners were used for the experiments named 1-nozzle burner and 6-nozzle burner (number of air supplies). Both burner types, shown in Fig. 17, could operate in flame and flameless oxidation mode by switching the gas supply. In flame mode, the 1-nozzle burner operates just like a standard high velocity burner. The gas is injected radially into the stream of preheated air, creating a stabilized flame that is entering the combustion chamber with a high velocity. The temperature distribution, shown in Fig. 18 show high temperatures at the burner discharge. The measurement had to be interrupted when the probe approached the burner discharge to a distance of 200 mm because the thermocouple was melted. When switching to flameless operation mode, the gas is injected axially, parallel to the high velocity air stream. The near burner temperature field changes significantly to a smooth temperature increase in the combustion chamber. The characteristic of the temperature field agreed well with the calculated

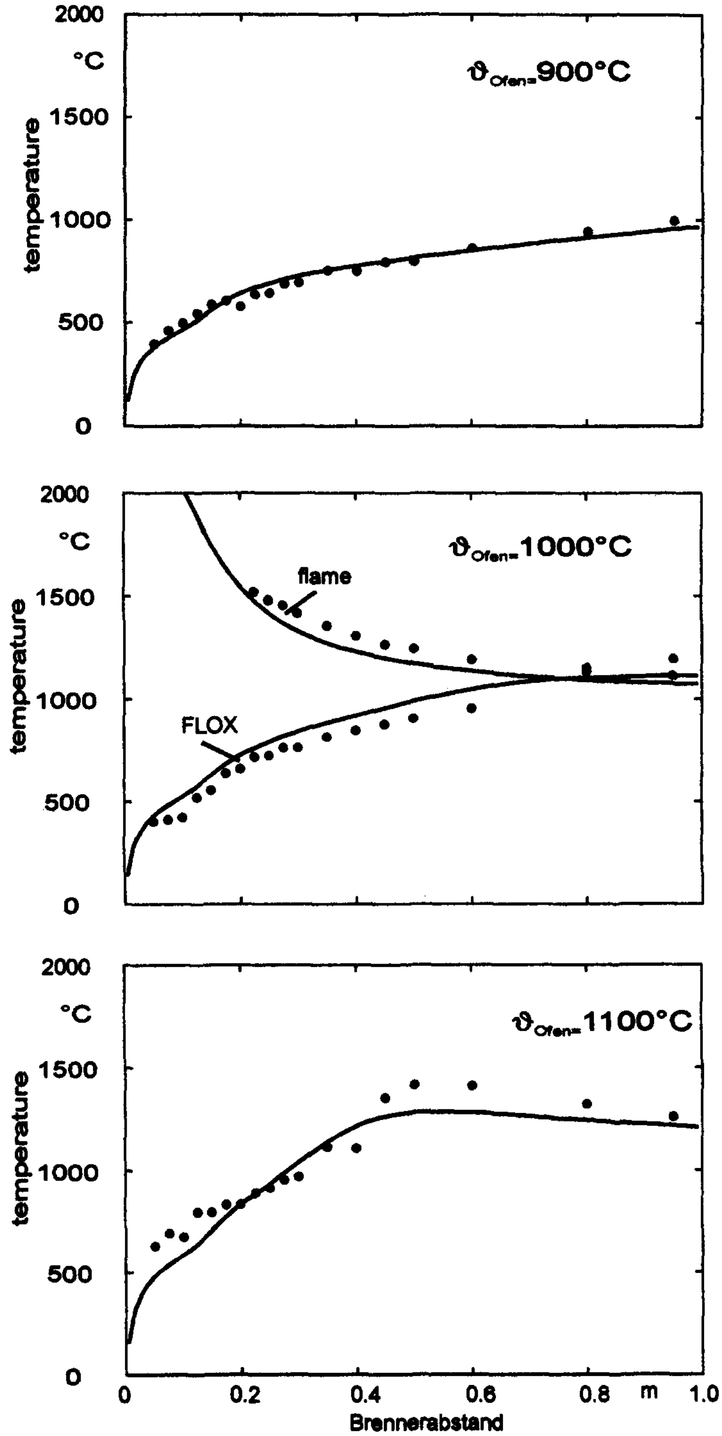

Fig. 19. Measured and calculated axial temperature distribution.

data, shown in Fig. 15. It could be also seen, that the temperature field apart the near burner region is hardly affected from the different combustion modes. Another form of presentation of the temperatures is given in Fig. 19. Axial temperature distributions are plotted for three mean chamber temperatures. The full line represents calculated data, the dots represents measured data. There is a good agreement for measured and calculated data for the flameless oxidation mode. For the flame mode, comparison could be done only for the postcombustion zone, due to the lack of measuring ability in the flame.

The other burner that was tested was the 6-nozzle burner. In flame mode, the gas is injected radially into the air stream. Combustion takes place behind a nozzle plate, through which the still reactive

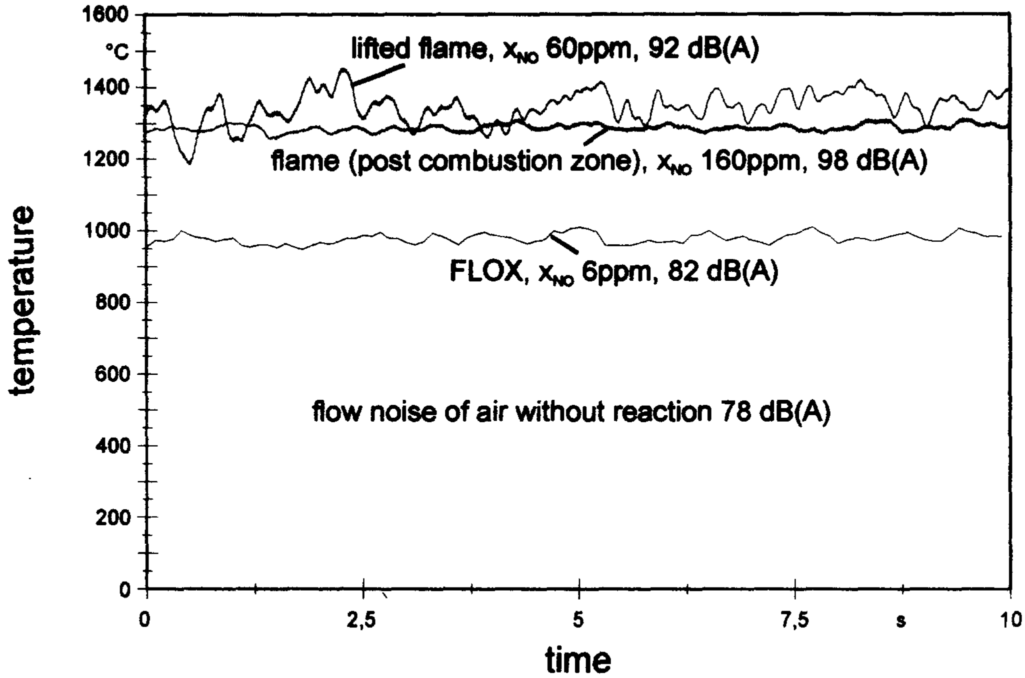

Fig. 20. Time history of temperatures.

combustion products enter the chamber. In flameless oxidation mode, the gas is supplied axially through the central gas nozzle and the air is injected through six concentric arranged nozzles. Because of the distance of gas and air supply, the reaction could only take place further downstream, when a large amount of exhaust has already mixed in. With a modification of inlet velocities this burner could be operated also with a unstable, lifted off flame. Results of the reading of the temperature history are shown in Fig. 20. The temperatures where measured in the burner axes at a distance of 250 mm from the burner discharge. That location represents the postcombustion zone for the flame mode and in flame measurement for the lifted flame. The temperature readings show similar behaviour for the flameless oxidation mode and for the postcombustion zone at flame mode at different temperature levels. Turbulent fluctuations are quite low. High fluctuations of low frequency were detected from the lifted flame what corresponds also to the visual impression of that combustion mode. Simultaneous to the temperature measurements, the noise level and the NO-emissions were recorded.

At a base flow level of ~80 dB(A), the reaction in flame mode increased that level to about 100 dB(A), the lifted flame created a noise level of ~90 dB(A) while the combustion noise at flameless oxidation mode was in the range of the base flow level. A large effect of combustion mode on the NO-emissions was measured. In flame mode, NO-emissions of 160 ppm were recorded. That is already a low figure, related to the present air preheat of 600°C and it could be achieved by flame cooling with the nozzle plate. In flameless oxidation mode the emissions could be reduced to emissions of 6 ppm at furnace mean temperatures of 1000°C and to figures < 2 ppm for furnace mean temperatures of 900°C.

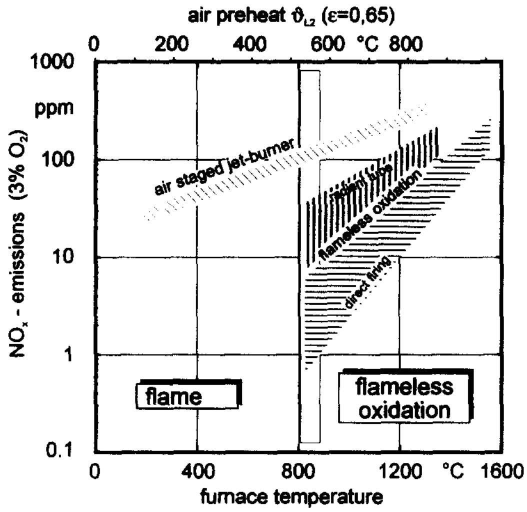

Fig. 21. NO_x-emission, collected data from various applications.

Figure 21 shows the NO-emission from various test facilities and industrial applications in a logarithmic scale diagram for different furnace temperatures. The burner capacity range reaches from 6 to 250 kW (natural gas). The most often used air preheat, related to the furnace temperature is shown on the upper side of the diagram. The upper band shows typical emission from an air staged, high velocity burner. At a temperature of about 850°C, burners can be switched to flameless oxidation mode. For direct fired

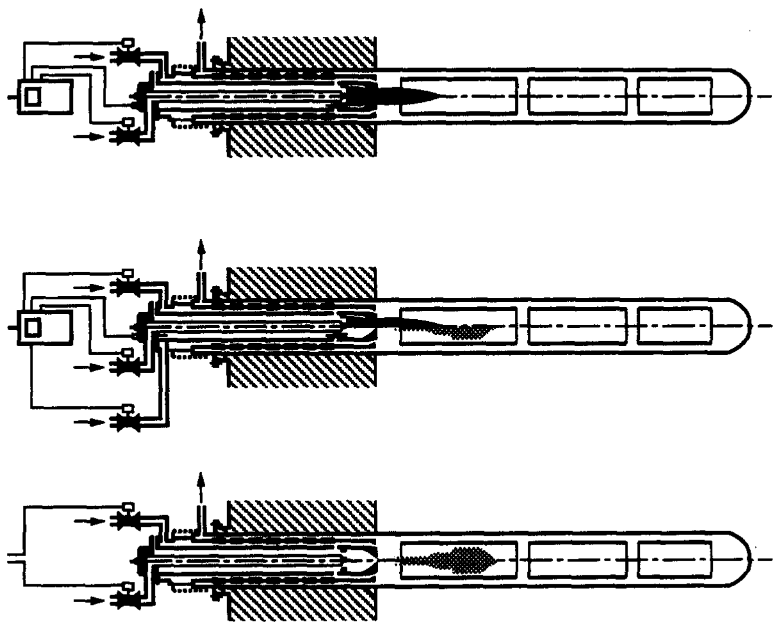

Fig. 22. Recuperative burner for use in radiant tubes.

applications, the NO-emissions can be reduced by one or two orders of magnitudes and can be lower than emissions from low temperature applications. That fact stimulates thoughts of using flameless oxidation even for lower process temperatures. In those cases the expenditures of operating the high temperature combustion chamber, necessary for flameless oxidation, has to be considered carefully against expenditures of other NO_x-reducing techniques. For narrow flow conditions (lower band in the diagram, Fig. 21), like they occur in radiant tubes, the reduction by switching from flames to flameless oxidation is still considerable.

5. APPLICATION EXAMPLES

The use of flameless oxidation is especially interesting, if high air preheat temperatures exists. For that reason, burners have been developed for use of preheated air and burners with integrated recuperative or regenerative heat exchangers.[23] Related to high temperature applications, there are additional aspects of flameless oxidation beside NO-formation. In general, burners have to be equipped with a flame supervision to avoid the emission of unburnt gases and the risk of explosion. Detectors for ionisation current or UV-signals are used. Flameless oxidation provides no signal for these detectors and until now, no commercial flame detector was found that is able to receive a signal from the reaction zone of flameless oxidation. In agreement with rules for atmosphere furnaces (furnaces which contain a special atmosphere, e.g. a hydrogen/nitrogen mixture), flame supervision could be switched off, if the furnace temperature is controlled to be at a level above self ignition temperature.

A point of interest is, that flameless oxidation requires no ignition, due to high combustion chamber temperatures. Both, ignition and flame supervision are often the reason for susceptance to failures of combustion systems and are not necessary at flameless oxidation mode. Another difference of practical relevance is the prevention of hot spots at the burner discharge. Usually, flames are located near to the burner or even in the burner, creating high thermal stresses and material fatigue. At flameless oxidation mode, the reaction will take place at some distance from the burner and the burner itself will be cooled by the combustion air.

Until now, burners operating in flameless oxidation mode have been used in industrial applications, mainly in the steel industry. These burners and their applications will be decribed in the following paragraphs. Successful tests were also carried out with stirling engines, at a protoytype level, which need an efficient external heat source at a temperature of 600–900°C.

5.1. *Recuperative Burners*

Recuperative burners are widely used in the steel industry for direct heating of industrial furnaces and in combination with radiant tubes for indirect heating. For different applications, the following burner configurations could be used (see Fig. 22).

(a) *Burner for flame mode only*

If the burner is operating most of the time in a low temperature range. The burner must be equipped with an ignition and flame supervision device.

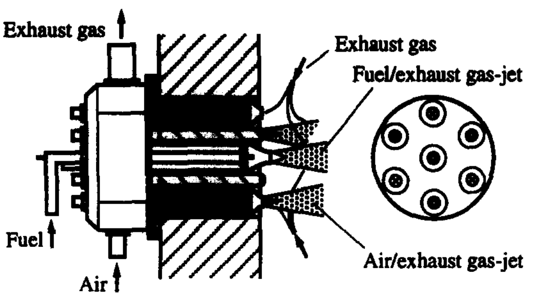

Fig. 23. Regenerative burner.

(b) *Burner for flame and flameless oxidation mode*

If the process is operating at high temperatures most of the time, but the burner must be able to heat up the combustion chamber, the burner must be able to operate in flame and flameless oxidation mode. Compared to the burner type (a), this burner has to be equipped with an additional gas supply and gas valve. The process control must provide a safe temperature control to avoid flameless oxidation mode at low temperatures.

(c) *Burner for flameless oxidation mode*

If the process is running at high temperatures all the time or when it is heated up with an external source, burners operating in flameless oxidation only mode could be used. The burner configuration for flameless oxidation mode only could be very simple, because no ignition and no flame supervision are necessary. Process control must ensure that the burner is switched off at low temperatures.

A very cost-effective way is the combined using of burners type (b) and (c) in a relation, depending on the required heat up time.

The low NO emissions, measured for recuperative burner in the test facility were confirmed by industrial applications. An example is the usage of flameless oxidation burners as radiant tube burners. Recuperative burners are working in a continuous strip line for the heat treatment of electrical sheets. At an operating temperature of 1000°C and air preheat temperature of 650°C the NO-emissions of these burners are 22–27 ppm (3% O_2).[24]

5.2. *Regenerative Burners*

Considerable energy savings are possible with the use of regenerative burners.[25] A main parameter for a high efficiency of a heat exchanger is the surface area. For recuperative designs, the costs increase about linear with the surface area. That cost limitation could be overcome, if regenerative heat exchangers are used. There the character of the heat exchanger surface is no longer two-dimensional. While there is no longer a need for a sealing between two media flows, three-dimensional structures can be used and the costs for additional surface area become little and heat exchangers with a large surface area are compact.[26]

A burner, using flameless oxidation is shown in Fig. 23. The following data were collected from tests:

nominal capacity	200 kW
air factor λ	1.1
fuel	natural gas
furnace temperature	up to 1300 °C
air preheat temperature	800–1050°C
efficiency	77–82 %
exhaust gas temperature	160°C
NO_x (5% O_2)	30–80 ppm.

The regenerators are arranged around a central fuel nozzle and a high velocity burner for start-up. Ceramic nozzles are connected to the regenerators which are filled with special material that store the heat from the exhaust gas and transfer it to the combustion air in the next cycle. Three regenerators heat the combustion air, while the other three cool down the exhaust gas. A typical switching time period is 20 s. The burner contains all parts of a regenerative system in one compact unit, including a cold air burner with ignition and control devices, regenerators and valves. The compact design and the arrangement of the regenerator minimize heat losses.

6. SUMMARY AND CONCLUSIONS

The main features of flameless oxidation could be summarized as follows:

- thermal NO-formation can be suppressed even at high air preheat temperatures;
- flameless oxidation is possible for combustion chamber temperatures, higher than 800°C (depending on fuel and combustion device);
- at optimized conditions, flameless oxidation occurs without any visible or audible appearance;
- flameless oxidation is possible in adiabatic and nonadiabatic combustion chambers;
- flameless oxidation requires high recirculation rates;
- in contrast to flames, no high gradients of temperature and species concentration exist;
- flameless oxidation can be calculated with existing, available simulation software;
- with the exception of the burner near field, temperature and flow conditions in the combustion chamber are similar for high velocity flame and flameless oxidation burners.

Due to the lack of high gradients, as found in flames, the use of flameless oxidation for analysis of chemical kinetic data and verfication of mathematical combustion models appears to be promising.

Until now, flameless oxidation has been applied in gas-fired industrial furnaces. The achievable NO-emissions request further research to explore other fields of usage. Investigation with laser techniques to detect reactive intermediates should provide more information about the process of flameless oxidation.

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